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# Tetravalent Chromium ( $\text{Cr}^{4+}$ ) as Laser-Active Ion for Tunable Solid-State Lasers

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## SEMI-ANNUAL PROGRESS REPORT

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## ACCOMPLISHMENTS

During 3/31/92 - 10/31/92 the following summarizes our major accomplishments made under the NASA grant: NAG-1-1346

Generation of **femtosecond** pulses from a continuous-wave mode-locked chromium-doped forsterite ( $\text{Cr}^{4+}:\text{Mg}_2\text{SiO}_4$ ) laser has been accomplished. The forsterite laser was actively mode-locked using an acousto-optic modulator operating at 78 MHz with two Brewster high-dispersion glass prisms for intra-cavity chirp compensation. Transform-limited sub-100-fs pulses were routinely generated in the  $\text{TEM}_{00}$  mode with 85 mW of continuous power (with 1% output coupler), tunable over 1230-1280 nm. The shortest pulses of 60-fs pulsewidth were measured.

## ABSTRACTS AND PRESENTATIONS

Several papers were published and presented during the covered period of this report:

1. A. Seas, V. Petričević, and R. R. Alfano, "Generation of Sub-100-fs Pulses From a Continuous-Wave Mode-Locked Chromium-Doped Forsterite Laser", postdeadline paper presented at the Conference on Lasers and Electro-Optics (CLEO), Anaheim, California, May 11-15, 1992.
2. A. Seas, V. Petričević, and R. R. Alfano, "Generation of Sub-100-fs Pulses From a Continuous-Wave Mode-Locked Chromium-Doped Forsterite Laser", *Opt. Lett.*, Vol. 17, pp. 937 (1992).
3. V. Petričević, A. Seas, and R. R. Alfano, "Novel  $\text{Cr}^{4+}$ -Based Tunable Solid-State Lasers", *Recent Advances in the Uses Of Light in Physics, Chemistry, Engineering and Medicine*, Daniel L. Akins and Robert R. Alfano, Editors, Proc. SPIE 1599, pp. 209-215 (1992).
4. A. Seas, V. Petričević, and R. R. Alfano, "60-fs Chromium-Doped Forsterite ( $\text{Cr}^{4+}:\text{Mg}_2\text{SiO}_4$ ) Laser ", postdeadline paper presented at the International Conference Ultrafast Phenomena VII, Antibes-Juan les Pins, France, June 8-12, 1992.
5. A. Seas, V. Petricević, and R. R. Alfano, "CW Mode-Locked Chromium-Doped Forsterite Laser Generates Tunable Sub-100-fs Pulses", presented at the 1992 Annual Meeting of the

## **RESEARCH PROGRAM**

### **CHROMIUM-DOPED FORSTERITE LASER GENERATES FEMTOSECOND PULSES**

The generation of femtosecond pulses from a continuous-wave mode-locked chromium-doped forsterite ( $\text{Cr}^{4+}:\text{Mg}_2\text{SiO}_4$ ) laser was accomplished. The forsterite laser was actively mode-locked using an acousto-optic modulator operating at 76 MHz with two Brewster high-dispersion glass prisms for intra-cavity chirp compensation. Transform-limited sub-100-fs pulses were routinely generated in the  $\text{TEM}_{00}$  mode tunable over 1230-1280 nm. The shortest pulses of 60-fs pulsewidth were measured and for the first time the forsterite laser operated in the self-mode-locked mode.

The experimental arrangement is shown in Fig. 1. The Brewster-angle-cut forsterite crystal was placed in a four-mirror, z-fold astigmatically compensated cavity which is widely used for Ti:sapphire lasers. The combination of mirrors used was: a flat back mirror, two 10-cm-radius folding mirrors, and a flat output coupler. The transmission of the output coupler was 1% at the lasing wavelength, while the folding mirrors and the back mirror had reflectivity  $R=99.9\%$  for the 1200-1300 nm range. The Cr:forsterite crystal used in this study was grown by the Mitsui Mining & Smelting Company, Japan. The length of the sample was 1 cm and the absorption coefficient at the pump wavelength of 1064 nm was  $\alpha = 0.7224 \text{ cm}^{-1}$ . To eliminate the need to chop the pump beam, the laser crystal was mounted in a copper block and was cooled by a single-stage thermoelectric cooler. Better thermal contact between the crystal and the copper block was achieved by wrapping the crystal in an indium foil. The crystal and the copper block were purged by nitrogen to prevent moisture condensation. The Cr:forsterite crystal was pumped by a continuous-wave Nd:YAG laser. The pump beam was focused by a 7.5-cm lens through the 10-cm-radius

folding mirror into the crystal. The 1064-nm pump power incident on the forsterite crystal was 4.7 W. The output of the forsterite laser was monitored with a fast germanium detector and an oscilloscope, and the pulsewidth was measured with a real-time autocorrelator. The bandwidth of the mode-locked forsterite laser was measured using a lead sulfide (PbS) detector coupled to a 50-cm Jarrel Ash monochromator, equipped with 10- $\mu$ m slits.

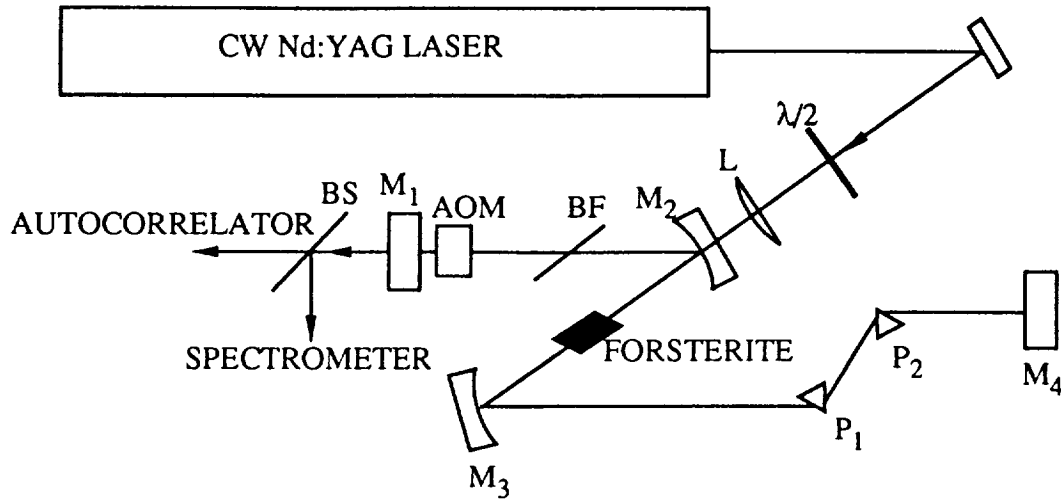


Fig. 1. Schematic diagram of the experimental arrangement for the actively mode-locked operation of the Cr:forsterite laser:  $\lambda/2$ , half-wave plate for 1064 nm; L, focusing lens; M<sub>1</sub>, output mirror, M<sub>2</sub>, M<sub>3</sub>, 10-cm-radius folding mirrors; M<sub>4</sub>, back mirror; AOM, acousto-optic modulator; BF, birefringent tuning plate; BS, beam splitter; P<sub>1</sub> and P<sub>2</sub>, Schott SF 14 glass prisms.

Actively mode-locked operation of the forsterite laser was achieved when the acousto-optic modulator was inserted in the cavity. Mode-locking was observed when the length of the cavity was adjusted to a length of  $\sim 1.97$  m corresponding to the frequency of the acousto-optic modulator (76 MHz). When the prisms are not part of the cavity a stable train of 6-ps pulses was obtained

with a bandwidth-pulsewidth product of 1.34 indicating that the pulses were chirped.

To compensate for the dispersion, a pair of high-dispersion Schott SF 14 glass Brewster prisms were inserted in the cavity. A pair of prisms was expected to introduce negative group-velocity dispersion, without increasing the cavity loss. The distance between the prisms was varied until the shortest pulse width were measured, while maintaining the total length of the cavity constant.

The insertion of the pair of SF 14 prisms in the cavity resulted in a significant reduction of pulsewidth. We observed two distinct regimes where the forsterite laser would produce femtosecond pulses. In the first regime we had compensation of GVD introduced by the forsterite crystal. The shortest pulses measured in this case had duration of 900 fs FWHM and spectral width of 1.9 nm FWHM. Figure 2 (a) shows the autocorrelation trace of the pulsewidth and figure 2 (b) shows the corresponding spectrum for the 900 fs pulses. Circles represent experimental data and the solid line is the best fit  $\text{sech}^2$  pulse shape was assumed for fitting. The pulsewidth-bandwidth product  $\Delta\tau_p\Delta\nu = 0.33$ , indicated nearly transform limited pulses.

Further optimization of the cavity (optimize the position of the forsterite crystal with respect to the two folding mirrors and the distance between the two folding mirrors) resulted in a significant reduction of pulsewidth, to less than 100 fs, with a spectral width of the order of 20 nm. An autocorrelation trace and the corresponding spectrum of a typical pulse are shown in figure 3 (a) and (b). The pulsewidth shown is 90 fs and the bandwidth is 19 nm. The pulsewidth-bandwidth product  $\Delta\tau_p\Delta\nu = 0.32$ , indicating transform-limited pulses for a  $\text{sech}^2$  pulse. The optimum distance between the two prisms when stable 90-fs pulses were obtained, was determined to be 35 cm. Shorter pulses were observed after long hours of cavity optimization and only for brief times. The autocorrelation trace presented in figure 4 shows a pulse of less than 60 fs FWHM.

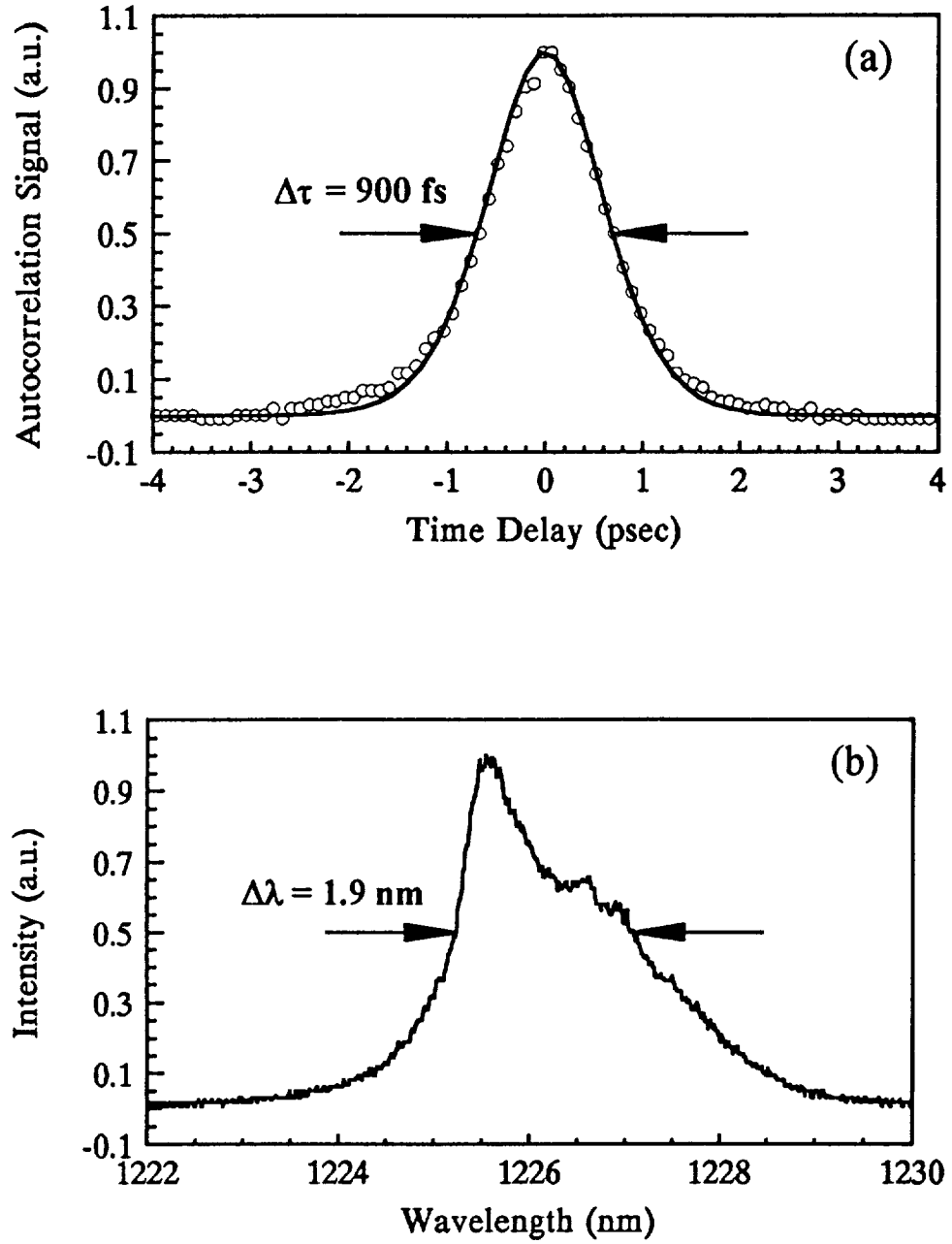


Fig. 2. An autocorrelation trace (a) and spectrum (b) of the 900 fs pulses. Circles represent experimental data and the solid line is the best fit.  $\text{sech}^2$  pulse shape was assumed for fitting. The pulsewidth-bandwidth product is  $\Delta\tau_p\Delta\nu = 0.33$ .

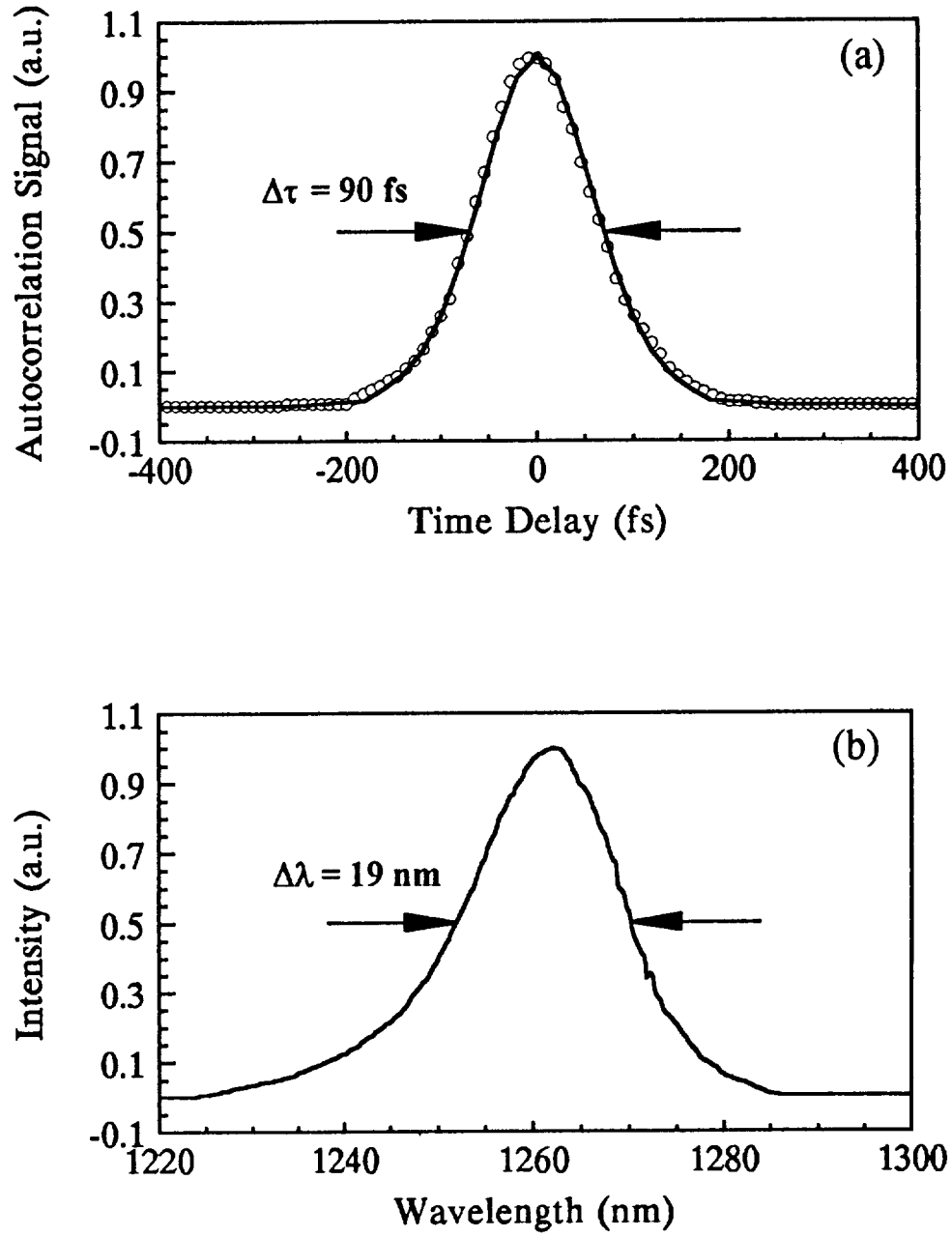


Fig. 3. An autocorrelation trace (a) and spectrum (b) of 90-fs pulses. Circles represent experimental data and the solid line is the best fit.  $\text{sech}^2$  pulse shape was assumed for fitting. The pulsewidth-bandwidth product  $\Delta\tau_p\Delta\nu = 0.32$ .

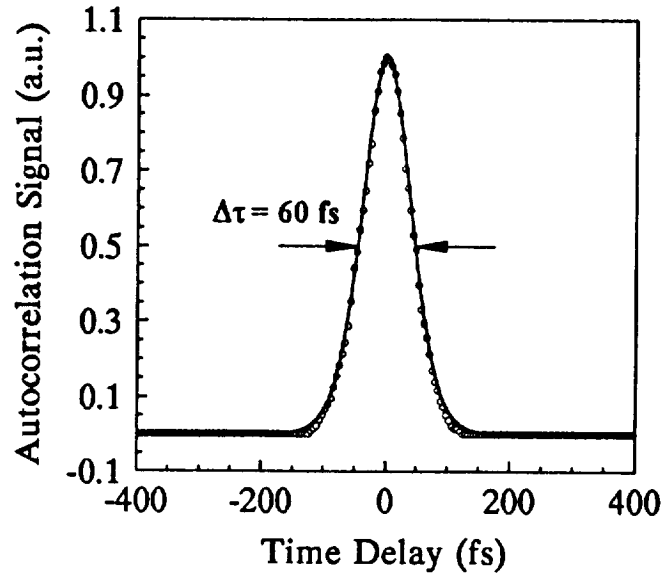


Fig. 4. An autocorrelation trace of 60-fs pulses (assuming  $\text{sech}^2$  pulse shape). Circles represent experimental data and the solid line is the best fit.

The reduction of the pulsewidth from 900 fs to 90 fs indicated that another mechanism besides active modulation is responsible for the shortening of the pulses. It was suspected that the self mode-locking mechanism was responsible for the generation of the 90 fs pulses. To investigate this possibility the RF power from the acousto-optic modulator was disconnected while stable sub-100-fs pulses were monitored. Within the first 30 seconds no change in the output was observed, i. e. stable sub-100-fs pulses were generated without any external modulation. The mode-locked operation usually ceased after this initial period, most likely due to some mechanical disturbances (Self mode-locking will be discussed in subsequent sections). This is an indication that the Cr:forsterite laser actually operated, similar to Ti:sapphire lasers in a self-mode locked regime, where active mode-locking only sets the conditions necessary for self-mode-locked operation by producing intense optical fields in the cavity. Intensity-induced Kerr nonlinearities in the gain medium, combined with negative group velocity dispersion introduced by the prisms are



responsible for production of the shortest pulses.

The actively mode-locked forsterite laser was tuned using an intracavity single-crystal quartz birefringent plate as shown in figure 1. With only one combination of laser mirrors the laser output was continuously tuned between 1230 - 1280 nm. The power output of 50 mW was measured, for 1.9 W of absorbed pump power. The pulsewidth and output power did not change significantly over the tuning range.

The dependence of the pulsewidth on the pump power was measured. As described above, when pumped by the maximum available power of 4.7 W incident on the crystal, stable sub-100-fs pulses were generated. As the pump power was lowered, the pulsewidth increased to above 1 ps at 3.9 W pump power incident on the forsterite crystal. The tendency of pulse shortening with increasing power suggests that, if more pump power were available, even shorter pulses may be obtained.